

PHENIX Measurements of Azimuthal Anisotropy for π^0 Production at High p_T in Au+Au Collisions at $\sqrt{s_{NN}} = 200\text{GeV}$

Rui Wei^a for the PHENIX collaboration

^aChemistry Department, Stony Brook University, Stony Brook, NY 11794, USA

Abstract

An improved measurement of v_2 for π^0 in a broad range of p_T and centrality is presented. By combining v_2 with the R_{AA} , we provide new insights on jet-medium interactions. We show that current pQCD energy loss models cannot describe the suppression of the π^0 as a function of the angle with respect to the reaction plane. Our result could help to resolve the factor of 4 differences in the predicted transport coefficients among these models. Alternatively, it may suggest that non-perturbative effects associated with the strongly coupled QGP are important, and new theoretical developments are needed to fully understand the jet medium interactions.

The measurement of π^0 anisotropy at PHENIX potentially serves three important goals for heavy-ion program at RHIC: a) to better constrain the energy loss processes by studying the suppression of π^0 as function of angle to the reaction plane (RP); b) to investigate the mechanisms for anisotropy at intermediate p_T , where the transition from a pressure gradient dependent outward-push driven by collective flow to a path length dependent attenuation driven by jet quenching takes place; c) to understand the non-flow contribution, especially those from jets, in the high p_T v_2 measurements. These goals are motivated by the current limitation in our understanding of the interactions between jets and flowing medium. For example, the extraction of transport properties suffer from large theoretical uncertainties. Predictions by various jet quenching frameworks differ by a factor of 4, even though they all describe the R_{AA} measurements with identical 3-D hydro evolution of the underlying medium [1]. Precision measurements of RP dependent suppression can provide severe constraints on these models.

These goals are facilitated by the large increase in the effective statistics of the 2007 Au+Au dataset from PHENIX, which is the basis of current analysis. It has two important improvements over the previous PHENIX measurements [2, 3]: 1) various new RP detectors were installed covering a broad η range with improved resolution (RxnPin, RxNPout, MPC at $1.0 < \eta < 1.5$, $1.5 < \eta < 2.8$ and $3 < \eta < 4$, respectively), and 2) factor of 4 increase in collected statistics relative to [3]. This is equivalent to an effective factor of 14 and 7 increase for π^0 v_2 measurement for RxNP and MPC, respectively. Due to limited space, we shall focus our discussion on goal a) and briefly mention goals b) and c) at relevant places.

The analysis follows the same technique laid out in [3]. The main idea is to extract π^0 's from the invariant mass distribution constructed separately in six bins of π^0 angle relative to the event plane (EP), $\Delta\phi = \phi_{\pi^0} - \Psi_{EP}$, in the interval $\Delta\phi \in [0 - \pi/2]$. The raw v_2 is obtained by fitting the raw yield with $A(1 + 2v_2^{raw} \cos 2\Delta\phi)$, which is then corrected by the corresponding reaction plane resolution, σ_{RP} , to give the signal $v_2 = v_2^{raw}/\sigma_{RP}$. Note that the EP is obtained via standard event plane method and σ_{RP} is measured via the sub-event method by correlating the north and south

RP detectors (which are symmetric). The differential nuclear modification factor $R_{AA}(\Delta\phi_i, p_T)$ is calculated from the published angle-averaged $R_{AA}(p_T)$ [4] as

$$R_{AA}(\Delta\phi_i, p_T) = R_{AA}(p_T) \frac{N(\Delta\phi_i, p_T)}{\langle N(\Delta\phi, p_T) \rangle} \frac{1 + 2v_2 \cos 2\Delta\phi_i}{1 + 2v_2^{raw} \cos 2\Delta\phi_i}. \quad (1)$$

One advantage of the broad η coverage for the RP detectors is that one can evaluate the potential non-flow effects. Figure 1 shows the v_2 vs N_{part} in a low p_T region and a high p_T region, measured by different RP detectors. There is a clear η dependence of v_2 values at high p_T , especially in the peripheral collisions. This is not the case at low p_T . This suggests that most of the non-flow effects are induced by jets, and they only become important at high p_T and for RP detectors reside closer to central arm where the π^0 s are detected. Even though RxNP detectors have the best resolution, they may suffer jet bias. Instead, we use MPC for EP determination. The MPC sits at the same η range as BBC detectors (used in previous analysis); however it has 40% better resolution compare to the BBC since it measures both neutral and charged particles, and has higher granularity.

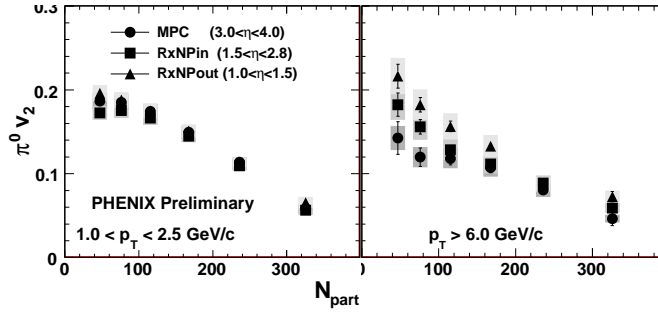


Figure 1: v_2 vs N_{part} at a low p_T and a high p_T regions using different reaction plane detectors.

Figure 2 shows v_2 values measured in six centrality classes, overlaid with the published results from 2004 Au+Au run [3]. The two measurements are consistent, but new data improve significantly on both statistical errors and p_T reach. The v_2 at $p_T > 6$ GeV/c, for all centralities, remains significantly above zero and is constant with p_T .

If the particle production at high p_T (> 6 GeV/c) is dominated by fragmentation of the jets that survive the medium, as most energy loss models predict, then it would lead to an anisotropy of the suppression which can be compared with our data. Figure 3 shows the high p_T R_{AA} for π^0 measured in-plane ($0 < \Delta\phi < \pi/12$) and out-of-plane ($5\pi/12 < \Delta\phi < 6\pi/12$) directions, derived according to Eq. 1. A clear split of the suppression levels can be seen between the two for three centrality bins shown (20-30%, 30-40% and 40-50%). Calculations from three pQCD jet quenching models (abbreviated as AMY, HT, ASW) from [1] are compared with our data. These calculations are carried out with identical initial conditions, medium evolution and fragmentation functions, and their suppression levels have been tuned to reproduce the inclusive R_{AA} data in central Au+Au collisions as well as the 20-30% bin. However, as Figure 3a shows, all three models under-predict the difference between in-plane and out-of-plane R_{AA} : The AMY model describes the out-of-plane R_{AA} , but not the in-plane; HT model is the opposite; ASW model does a reasonable job for both in- and out-of plane directions at high p_T , but misses the low p_T region. However, we are not advocating that one model is better than the other, because changing other control parameters, like initial conditions, medium evolution or fragmentation functions, may change this comparison. Our principal conclusion is that by utilizing both observables, one

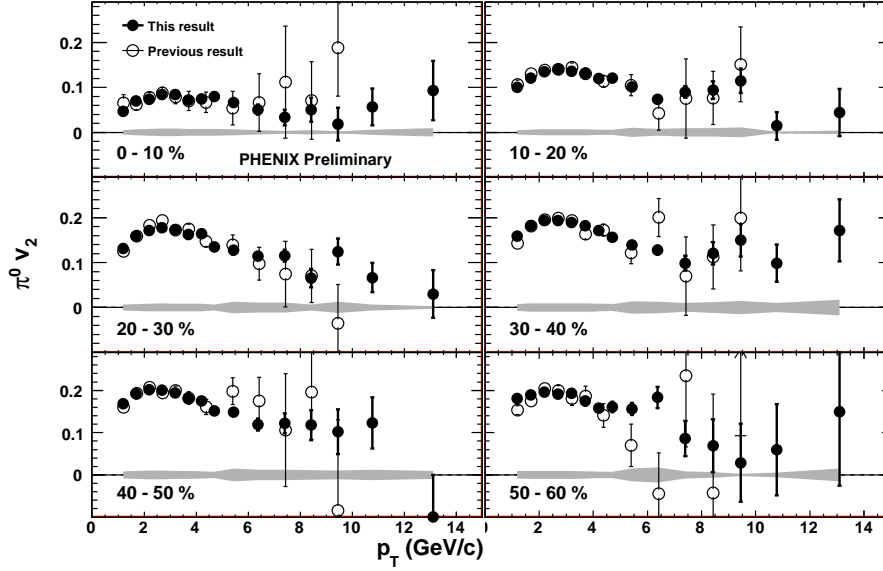


Figure 2: $\pi^0 v_2$ vs p_T in six centrality bins. The solid points are the PHENIX preliminary results in Run 7 measured with the MPC detector. The open points are the published results from [3].

should be able to narrow down the uncertainties on initial condition and medium evolution and other effects that were ignored so far in the calculation, e.g. virtuality difference between the in- and out-of plane. Our data may help to resolve the discrepancies, e.g. \hat{q} , between the model predictions.

On the other hand, the failure of these models to reproduce the large anisotropy at high p_T may imply that the pQCD treatment of the energy loss process as sequential radiation, being proportional to the local color charge density is not sufficient. In the presence of the strongly coupled medium (sQGP), both the path length dependence and the color charge dependence could be modified. For example, calculation based on ADS/CFT technique suggests that $\Delta E \propto L^3$ [5] and $\hat{q} \propto \sqrt{\alpha_{SYM} N_c}$ [6] instead of $\Delta E \propto L^2$ and $\hat{q} \propto \alpha_s N_c^2$ for pQCD. In a separate calculation, Kharzeev [7] estimates $dE/dx \propto E^2$ in strong coupling limit, much stronger than the logarithmic dependence expected from pQCD. These non-linear dependences could be the reason for the large anisotropy. Figure 4 shows the comparison of v_2 with several toy model predictions with different medium density dependence. The model from [8] introduces strong non-linear dependence by assuming that jet quenching happens mostly close to phase transition boundary. The model from [9] does so by suppressing the energy loss at high energy density region by using a plasma formation time argument. Both are able to qualitatively describe centrality dependence. However, much need to be done to generalize these toy models into rigorous theoretical calculations.

In summary, we presented high statistics measurement of $\pi^0 v_2$ and $R_{AA}(\Delta\phi, p_T)$ up to 13 GeV/c in broad centrality ranges of Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Current energy loss models were not able to describe $R_{AA}(\Delta\phi, p_T)$ at $p_T > 6$ GeV/c. This discrepancy implies that the current pQCD models need further tuning, in which case our measurement can help to resolve the differences in these models. It may also suggest that the non-perturbative effects associated with

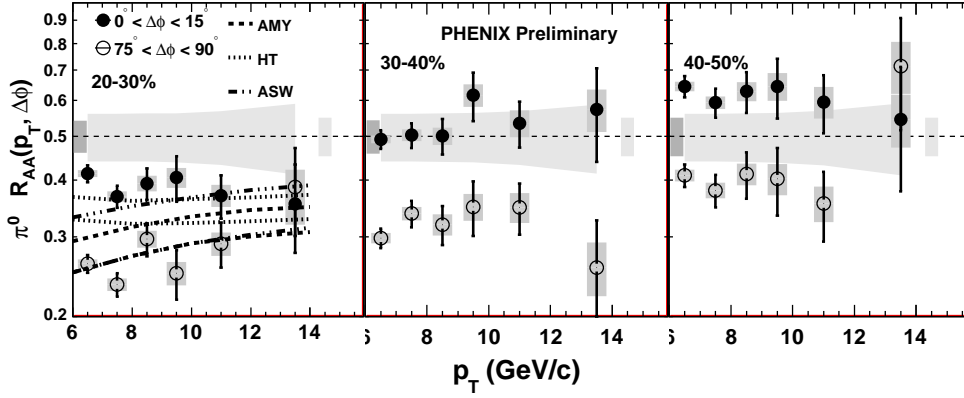


Figure 3: Data points: solid(open) is the in-plane(out-of-plane) $\pi^0 R_{AA}(p_T)$ for three centrality bins measured with the MPC detector. Lines represent calculations of AMY, HT and ASW models from [1], respectively.

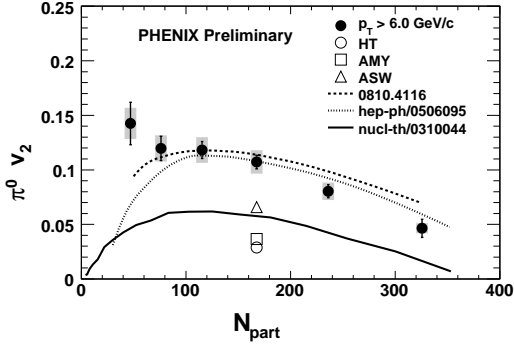


Figure 4: Data points: v_2 values at $p_T > 6\text{ GeV}/c$ measured with the MPC detector. Open symbols: pQCD model calculations taken from [1]. Lines: geometric model calculations with different assumptions on path length dependence [10, 9, 8].

the strongly coupled QGP are important, and new tools are required to understand the energy loss processes. Further detailed study of the v_2 and R_{AA} in the intermediate p_T range of 2-6 GeV/c may shed light on the role of perturbative and non-perturbative effects.

Acknowledgments

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